TRIGONAL INTERPRETATION OF RESERVOIR PERFORMANCE

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by

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B. S., University of California, 1934

Submitted to the Graduate School of the University of Pittsburgh in partial fulfillment of the requirements for the degree of Master of Science

Pittsburgh, Pennsylvania

1954

FOREWORD

The author of this thesis is a Commander in the United States Navy attending the Graduate School of the University of Pittsburgh under official orders from the Chief of Naval Personnel. In addition to his capacity as a graduate student at the University of Pittsburgh, he is also a student of the United States Naval Postgraduate School, Monterey, California.

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A. Interpretation and Prediction of Reservoir Performance

An analysis of the performance of a producing petroleum reservoir is the basis on which the Reservoir Engineer will make his recommendations for a production program that will yield the optimum economic return. His analysis will be based upon his knowledge and understanding of the effect of the lithology of the reservoir rock, the characteristics of the reservoir fluids and the forces which act to expel or produce the reservoir fluids.

One of the basic tools available to the Reservoir Engineer is the material balance equation developed by Schilthuis,[1] and modifications thereto. This material balance equation of Schilthuis' is so derived that it can account for any one, or any combination of the three components, oil, gas and water, that occupies the pore space of the reservoir. With proper use of this equation, the performance of a reservoir can be interpreted and predicted. The literature contains much information on the use of the material balance equation in the analysis of reservoir performance. Each analysis is usually accompanied by a series of charts and graphs to illustrate the performance of the reservoir. It is noted, however, that these charts and graphs deal only with the variation of two components, while the third component is ignored or considered to be constant.

The purpose of this paper is to present a new and different method of interpreting the performance of a producing petroleum reservoir by developing a means of illustrating the variations of the three components simultaneously, or in other words, to present a visual representation of the material balance.

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[1] References in Bibliography

I. INTRODUCTION AND DISCUSSION

A. Interpretation and Prediction of Reservoir Performance

An analysis of the performance of a producing reservoir is the basis on which the reservoir engineer will make his recommendations for a production program that will yield the optimum economic return. This analysis will be based upon his knowledge and understanding of the effect of the lithology of the reservoir rock, the characteristics of the reservoir fluids and the forces which act to expel or produce the reservoir fluids.

One of the basic tools available to the reservoir engineer is the material balance equation developed by Schilthuis[1] and [illegible]. This material balance equation of Schilthuis is so derived that it can account for any one, or any combination of the three mechanisms, oil, gas and water, that occupies the pore space of the reservoir. With proper use of this equation, the performance of a reservoir can be interpreted and predicted. The literature contains much information on the use of the material balance equation in the analysis of reservoir performance. This analysis is usually accomplished by a method of trial and error graphical [illegible] the reservoir. It is noted, however, that these trial and [illegible] with the variation of two parameters, while [illegible] are assumed to be constant.

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B. The Material Balance

Simply stated, a material balance is based on the premise that the amount originally present must equal the sum of the amount removed and the amount remaining. To obtain a material balance in the case of the petroleum reservoir, it is necessary to determine the original volume of each of the fluid components that occupied the virgin reservoir void space, measure the volume of each of the components that has been produced, and calculate the volume of each of the components remaining in the reservoir.

The void space in the petroleum reservoir is occupied by the three components, oil, gas and water, that must be accounted for in the material balance. The water exists as a liquid both in the reservoir and at the surface, and its volume changes only a negligible amount when it decompresses from reservoir pressure to surface pressure. The oil in the reservoir will contain dissolved gas. As this oil and dissolved gas is produced, the gas will evolve as the pressure reduces from reservoir pressure to surface pressure. The gas, when in the reservoir, may exist in two distinct states: as free gas under compression, and as gas dissolved in the oil. As the reservoir produces, the pressure on the produced fluids drops from reservoir pressure to surface pressure, dissolved gas comes out of solution in the produced oil and joins any free gas produced. All produced gas under surface pressure occupies a much larger volume than it occupied under reservoir pressure. In the development of the material balance for this paper, it is important that careful distinction be made between free gas and dissolved gas, and that the volumes of all components entering into this material balance be expressed in the same units and at reservoir conditions of pressure and temperature.

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The void space in the petroleum reservoir is occupied by the three components, oil, gas and water, that must be accounted for in the material balance. The water exists as a liquid both in the reservoir and at the surface, and its volume changes only a negligible amount when it is depressed from reservoir pressure to surface pressure. The oil in the reservoir will contain dissolved gas. As this oil and dissolved gas is produced, the gas will evolve as the pressure reduces from reservoir pressure to surface pressure. The gas, when in the reservoir, may exist in two distinct states: as free gas under compression, and as gas dissolved in the oil. As the reservoir produces, the pressure on the produced fluids drops from reservoir pressure to surface pressure, dissolved gas comes out of solution in the produced oil and joins any free gas produced. All produced gas under surface pressure occupies a much larger volume than it occupied under reservoir pressures. In the development of the material balance for this paper, it is important that careful distinction be made between free gas and dissolved gas, and that the volumes of all components entering into this material balance be expressed in the same units and at reservoir conditions of pressure and temperature.

C. The Driving Mechanisms

The fluids in the reservoir are produced or expelled from the reservoir by one or a combination of three driving mechanisms: water drive, dissolved gas or depletion drive, and expanding gas-cap or segregation drive. In all three mechanisms the driving force acts when there is a pressure differential within the reservoir.

Water drive occurs when there is edge-water encroachment due to artesian flow or expansion of the water on decompression.

Dissolved gas or depletion drive occurs when gas coming out of solution in the oil, due to reduction in reservoir pressure, expands and displaces the reservoir fluids.

Expanding gas-cap or segregation drive occurs when, upon reduction of reservoir pressure, the expansion of the free gas in the gas-cap displaces the reservoir fluids lying below the gas-oil interface in the reservoir.

II. STATEMENT OF THE PROBLEM

The void space in a producing petroleum reservoir is usually occupied by three components, (1) oil and dissolved gas, (2) free gas and (3) water. As production of the reservoir proceeds, the space vacated by the produced fluids must be filled by either expanding free gas or encroaching water, or both. While the volume of the void space remains constant during production, the volume of each of the components which occupies that void space is subject to change. The oil and dissolved gas volume will decrease as production proceeds. If the driving mechanism producing the reservoir is a gas drive and there is no water encroaching or being produced, the free gas volume will increase and the water volume will remain constant. If the driving mechanism is a water drive, the water volume will increase and the free gas volume will remain constant. If the driving mechanism is a combined water and gas drive, then both the water volume and the gas volume will increase.

The purpose of this study is to develop a visual representation of the performance of a petroleum reservoir by use of a trigonic graph, on which the per cent of the volume of void space occupied by each of the three components is shown at any time by a single point, and where a line plotted through successive points will indicate the trend of production of the reservoir.

An interpretation of the performance of the reservoir can be made from the trigonic plot and a production program that will yield the optimum economic return then can be planned.

II. STATEMENT OF THE PROBLEM

The void space in a petroleum reservoir is normally occupied by three components, (1) oil and dissolved gas, (2) free gas and (3) water. As production of the reservoir proceeds, the space vacated by the produced fluids must be filled by either expanding free gas or encroaching water, or both. While the volume of the void space remains constant during production the volume of each of the components which occupies that void space is subject to change. The oil and dissolved gas volume will decrease as production proceeds. If the driving mechanism producing the reservoir is a gas drive and there is no water encroachment or being produced, the free gas volume will increase and the water volume will remain constant. If the driving mechanism is a water drive, the water volume will increase and the free gas volume will remain constant. If the driving mechanism is a combined water and gas drive, then both the water volume and the gas volume will increase.

The purpose of this study is to develop a visual representation of the performance of a petroleum reservoir by use of a triangular graph, on which the per cent of the volume of void space occupied by each of the three components is shown at any time by a single point, as shown. A line plotted through successive points will indicate the trend of production of the reservoir.

An interpretation of the performance of the reservoir can be made from the triangular plot and a production program which will yield the optimum economic return then can be planned.

III. DEVELOPMENT OF THE TRIGONIC PLOT AS APPLIED TO THE RESERVOIR

A. Advantages and Disadvantages of the Trigonic Plot

In any situation or condition in which the sum of three variables, expressed in the same units, comprises the whole, if the values for two of the variables are known, the value of the third variable becomes immediately apparent, since the sum of the three must always equal unity or 100 per cent. This situation can be illustrated graphically by use of the trigonic plot. The trigonic graph is an equilateral triangle with each base representing zero per cent and each apex representing 100 per cent of one of the three components. Any point within the trigon will indicate the portion of the whole or the percentage that each variable contributes to the whole.

In the case of the petroleum reservoir, the total pore volume of the reservoir is taken as the reference basis and represents 100 per cent. This pore volume may be occupied by any combination of (1) oil and dissolved gas, (2) free gas and (3) water. When the degree of occupancy by these three components is expressed in terms of per cent saturation, the sum will equal 100 per cent. When the precentage saturation is related to and plotted on the trigonic graph, the degree of occupancy of all three components will be represented by a single point.

The disadvantage of the trigonic plot is that it gives relative and not actual values. Additional calculations are required to reduce actual values in terms of barrels and cubic feet to relative values in terms of per cent of pore volume. Conversely, in analysing and interpreting the trigonic plot for production or economic purposes, the relative values in terms of per cent must be converted into actual values in terms of barrels and cubic feet.

III. [illegible]

A. [illegible] advantages and disadvantages of the triangular plot

In any situation or condition in which the sum of three variables, expressed in the same units, comprises the whole, if two values for two of the variables are known, the value of the third variable becomes immediately apparent, since the sum of the three must always equal 100 per cent. This situation can be illustrated graphically by use of the triangular plot. The triangular graph is an equilateral triangle with each side representing zero per cent and each apex representing 100 per cent of one of the three components. Any point within the triangle will indicate the portion of the whole or the percentage that each variable contributes to the total.

In the case of the petroleum reservoir, the total pore volume of the reservoir is taken as the reference volume and represents 100 per cent. This pore volume may be occupied by any combination of (1) oil and dissolved gas, (2) free gas and (3) water. When the volume of each of these three components is expressed in terms of per cent saturation, the sum will equal 100 per cent. Thus the percentage saturation of each of the three components on the triangular graph, the degree of saturation of all three components will be represented by a single point.

The disadvantage of the triangular plot is that it gives ratios and not actual values. Additional calculations are required to express these values in terms of barrels and cubic feet [illegible] in the case of pore volumes. However, in analyzing the [illegible] plot [illegible] or reservoir [illegible] each made to [illegible] actual [illegible]

D. Effect of Driving Mechanism on Saturation

There are three driving mechanisms that singly or in combination will expel the reservoir fluids from the reservoir into the well: water drive, dissolved gas drive, and expanding gas-cap drive. In the case of a water drive, the decrease in oil and dissolved gas saturation is made up by a corresponding increase in water saturation. In the case of a gas drive, the decrease in the oil and dissolved gas saturation is made up by a corresponding increase in the free gas saturation. For a combined water and gas drive, the decrease in oil and dissolved gas saturation is made up by an increase in both the water saturation and the free gas saturation, the relative increase of each being proportional to the relative magnitude of the driving forces.

To present a trigonic illustration of the effects of driving mechanisms on the saturation of a reservoir, a theoretical reservoir has been assumed. This theoretical reservoir has the following original saturation condition:

Oil and Dissolved Gas Saturation	-	65 per cent
Water (Connate) Saturation	-	20 per cent
Free Gas (Gas Cap) Saturation	-	15 per cent

Point A on figure 1 represents the original saturation condition of this theoretical reservoir on a trigonic plot.

1. Gas Drive

There are two types of gas drive for producing a reservoir, expanding gas-cap, and dissolved gas drives. In the theoretical reservoir, assuming that no connate water is produced, the saturation picture as the reservoir is produced by a gas drive will follow the line AB in figure 1. That is, as each unit volume of oil and dissolved gas is produced or removed from the reservoir, the space occupied by this unit volume will be filled by free gas, the

F. Effect of Driving Mechanism on Saturation

There are three driving mechanisms that might be in operation which will expel the reservoir fluids from the reservoir into the well: water drive, dissolved gas drive, and expanding gas-cap drive. In the case of a water drive, the decrease in oil and dissolved gas saturation is made up by a corresponding increase in water saturation. In the case of a gas drive, the decrease in the oil and dissolved gas saturation is made up by a corresponding increase in the free gas saturation. For a combined water and gas drive, the decrease in oil and dissolved gas saturation is made up by an increase in both the water saturation and the free gas saturation, the relative increase of each being proportional to the relative magnitude of the driving forces.

To present a complete illustration of the effects of driving mechanisms on the saturation of a reservoir, a theoretical reservoir has been assumed. This theoretical reservoir has the following original saturation conditions:

Oil and Dissolved Gas Saturation - 75 per cent

Water (Connate) Saturation - 25 per cent

Free Gas (Gas Cap) Saturation - 0 per cent

Point A on Figure 1 represents the original saturation condition of this theoretical reservoir on a triangular plot.

1. Gas Drive

There are two types of gas drive for producing a reservoir, expanding gas-cap, and dissolved gas drives. In the [illegible] dissolved [illegible] which [illegible] in [illegible], the saturation [illegible] of the reservoir is produced by a gas drive which follows the line [illegible] Thus [illegible] and the oil and dissolved gas is [illegible] [illegible] [illegible] additional free gas required to occupy this space being supplied either by expansion of the gas-cap or by dissolved gas coming out of solution in the reservoir, or by a combination of both.

Let it be assumed that the oil and dissolved gas saturation is reduced from 65 per cent to 55 per cent by gas drive. If no water has been produced the water saturation remains at 20 per cent. Therefore, the free gas saturation must have increased from 15 per cent to 25 per cent in order to account for the total volume of the reservoir. On the trigonic plot of this reservoir (figure 1), this new saturation condition is represented by point b'.

If it so happens that some of the original connate water is produced or removed by the gas drive, then the line AB would be displaced to the left to indicate a decrease in both the water saturation and the oil and dissolved gas saturation.

2. Water Drive

If an ideal water drive situation is assumed for the theoretical reservoir, there will be no pressure drop in the reservoir, no expansion of the gas-cap, and no dissolved gas coming out of solution in the oil. Therefore, the space vacated by each volume unit of reservoir oil, with its dissolved gas still in solution, will be occupied by an equal volume unit of encroaching or driving water. The saturation picture as the reservoir is produced by the water drive will follow the line AD in figure 1.

Let it be assumed that the oil and dissolved gas saturation has been reduced from 65 per cent to 50 per cent by water drive. If the reservoir pressure has remained unchanged, the free gas (gas-cap) saturation remains at 15 per cent. Therefore the water saturation must have increased from additional free gas required to occupy this space must come either by expansion of the gas-cap or by dissolved gas coming out of solution in the reservoir, or by a combination of both.

Let it be assumed that the oil and dissolved gas saturation is reduced from 65 per cent to 55 per cent by gas drive. If no water has been produced the water saturation remains at 20 per cent. Therefore, the free gas saturation must have increased from 15 per cent to 25 per cent in order to account for the total volume of the reservoir. On the triangle plot of this reservoir (Figure 3), this new saturation condition is represented by point B.

If it so happens that some of the original connate water is produced or removed by the gas drive, then the line AB would be displaced to the left to indicate a decrease in both the water saturation and the oil and dissolved gas saturation.

2. Water Drive

If an ideal water drive situation is assumed for the theoretical reservoir, there will be no pressure drop in the reservoir, no expansion of the gas-cap, and no dissolved gas coming out of solution in the oil. Therefore, the space vacated by each volume unit of reservoir oil, with its dissolved gas still in solution, will be occupied by an equal volume unit of encroaching or driving water. The saturation picture as the reservoir is produced by the water drive will follow the line AC in Figure 3.

Let it be assumed that the oil and dissolved gas saturation has been reduced from 65 per cent to 50 per cent by water drive. If the reservoir pressure has remained unchanged, the free gas (gas-cap) saturation remains at 15 per cent. Therefore, the water saturation must have increased from

20 per cent to 35 per cent in order to account for the total volume of the reservoir. On the trigonic plot of this reservoir (figure 1) this new saturation condition is represented by point d'.

3. Combined Gas and Water Drive

In the combined gas and water drive situation, the gas drive is provided either by expansion of the gas-cap, or by expansion of the dissolved gas coming out of solution or by both. If the magnitudes of the water and gas driving forces are equal, then for each unit volume of reservoir oil produced, the space vacated by this unit volume will be half occupied by free gas of the expanding gas-cap and/or gas coming out of solution, and half occupied by encroaching or driving water. The saturation picture as the reservoir is produced by this combined drive will follow the line AC in figure 1. The same saturation picture would hold if the gas drive energy came from the expanding gas-cap only, and no gas came out of solution in the reservoir.

Let it be assumed that the oil and dissolved gas saturation has been reduced from 65 per cent to 45 per cent by a combined drive where the water drive and the gas drive are equal. Since the 20 per cent of the space vacated by the produced oil and dissolved gas is equally occupied by free gas and water, the saturation of each is increased by 10 per cent. Therefore, the free gas saturation becomes 25 per cent and the water saturation becomes 30 per cent. On the trigonic plot of this reservoir (figure 1) this new saturation condition is represented by point c'.

If, in a combined drive situation, the magnitudes of the driving forces are not equal, then the saturation picture will vary proportionally as the relative magnitude of the driving forces. If the magnitude of the water drive force exceeds that of the gas drive, then more oil and dissolved gas will be replaced by water than by free gas, or the increase in water saturation will be greater than the increase in free gas saturation. In this case, the

20 per cent to 35 per cent in order to account for the total volume of the reservoir. On the trigonic plot of this reservoir (Figure 1) this new saturation condition is represented by point d'.

3. Combined Gas and Water Drive

In the combined gas and water drive situation, the gas drive is provided either by expansion of the gas-cap, or by expansion of the dissolved gas coming out of solution or by both. If the magnitudes of the water and gas driving forces are equal, then for each unit volume of reservoir oil produced, the space vacated by this unit volume will be half occupied by free gas of the expanding gas-cap and/or gas coming out of solution, and half occupied by encroaching or driving water. The saturation picture at the reservoir is produced by this combined drive will follow the line OD in Figure 1. The same saturation picture would hold if the gas drive energy came from the expanding gas-cap only, and no gas came out of solution in the reservoir.

Let it be assumed that the oil and dissolved gas saturation has been reduced from 85 per cent to 45 per cent by a combined drive where the water drive and the gas drive are equal. Since the 40 per cent of the space vacated by the produced oil and dissolved gas is equally occupied by free gas and water, the saturation of each is increased by 20 per cent. Therefore, the free gas saturation becomes 25 per cent and the water saturation becomes 30 per cent. On the trigonic plot of this reservoir (Figure 1) this new saturation condition is represented by point e'.

If, in a combined drive situation, the magnitudes of the driving forces are not equal, then the saturation pictures will vary proportionally as the relative magnitudes of the driving forces. If the magnitude of the water drive force exceeds that of the gas drive, then more oil and dissolved gas will be replaced by water than by free gas, or the increase in water saturation will be greater than the increase in free gas saturation. In this case, the saturation picture would be represented on the trigonic plot by a line lying between lines AC and AD in figure 1. The greater the displacement of reservoir oil by the water, the closer this line will approach the line AD, the situation of ideal water drive. Conversely, if the gas drive force were to predominate, then the saturation line would lie between lines AC and AB in figure 1.

From the foregoing discussion, it can be postulated that lines AB and AD represent respectively the limits for ideal gas drive and ideal water drive. In other words, when the change in saturation follows line AD, the driving or displacing force is due entirely to water drive. When the change in saturation follows line AB, the driving or displacing force is due entirely to gas drive.

4. Determination of the Magnitude of Driving Forces from the Trigonic Plot

In the foregoing discussion, it has been established that the driving or displacing forces are limited by the ideal conditions represented by lines AB and AD. It is apparent that any combination of gas and water drive will result in a saturation line falling between these two limits. It is also apparent that the position of this line with respect to the two limiting lines will be an indication of the relative magnitude of the two driving forces with respect to each other.

In the case where the two driving forces are considered to be equal, resulting in the saturation line AC, the two driving forces each displace an equal amount of reservoir oil. When the amounts displaced by each driving force are considered as a ratio, a numerical indication of the magnitude of the driving forces results. In this case, the ratio of reservoir oil displaced by gas drive to reservoir oil displaced by water drive will be 1/1. This ratio will be called the Displacement Index.

The Displacement Index may then be expressed as the ratio of the change of gas saturation to the change of water saturation, that is:

$$DI = ds_g/ds_w$$

saturation picture would be represented on the triangular plot by a line lying between lines AC and AB in Figure 1. The greater the displacement of reservoir oil by the water, the closer this line will approach the line AB, the condition of ideal water drive. Conversely, if the gas drive force were predominant, then the saturation line would lie between lines AC and AD in Figure 1.

From the foregoing discussion, it can be postulated that lines AC and AB represent respectively the limits for ideal gas drive and ideal water drive. In other words, when the change in saturation follows line AB, the driving or displacing force is due entirely to water drive. When the change in saturation follows line AC, the driving or displacing force is due entirely to gas drive.

4. Determination of the Magnitude of Driving Forces from the Triangular Plot

In the foregoing discussion, it has been established that the driving or displacing forces are limited by the ideal conditions represented by lines AB and AC. It is apparent that any combination of gas and water drive will result in a saturation line falling between these limits. It is also apparent that the position of this line with respect to the limiting lines will be an indication of the relative magnitude of the two driving forces with respect to each other.

In the case where the two driving forces are considered to be equal, resulting in the saturation line AD, the two driving forces have displaced an equal amount of reservoir oil. When the amounts displaced by each driving force are considered as a ratio, a numerical indication of the magnitude of the driving forces results. In this case, the ratio of reservoir oil displaced by gas drive to reservoir oil displaced by water drive will be 1/1. This ratio will be called the Displacement Index.

The Displacement Index may then be expressed as the ratio of the change of gas saturation to the change of water saturation, that is:

$$DI = \Delta S_g/\Delta S_w$$

Referring to figure 1 and the case where the driving forces are equal, point c', the gas saturation changes from 15 per cent to 25 per cent and the water saturation changes from 20 per cent to 30 per cent, therefore:

$$DI = (25 - 15)/(30 - 20)$$
$$= 1/1$$

In the situation represented by point c", the gas saturation changes from 15 per cent to 35 per cent and the water saturation changes from 20 per cent to 25 per cent, therefore:

$$DI = (35 - 15)/(25 - 20)$$
$$= 4/1$$

In the situation represented by point c"', the gas saturation changes from 15 per cent to 20 per cent, and the water saturation changes from 20 per cent to 40 per cent, therefore:

$$DI = (20 - 15)/(40 - 20)$$
$$= 1/4$$

It is obvious, then, that a Displacement Index less than 1/1 will indicate a predominant water drive, while a Displacement Index greater than 1/1 will indicate a predominant gas drive.

In determining the Displacement Index from the change in saturation, it is necessary to take the different saturations in the proper vectorial direction, that is, the later saturation must be deducted from the earlier saturation. A negative Displacement Index will result when the free gas saturation is reduced by a water drive, or the water saturation is reduced by a gas drive.

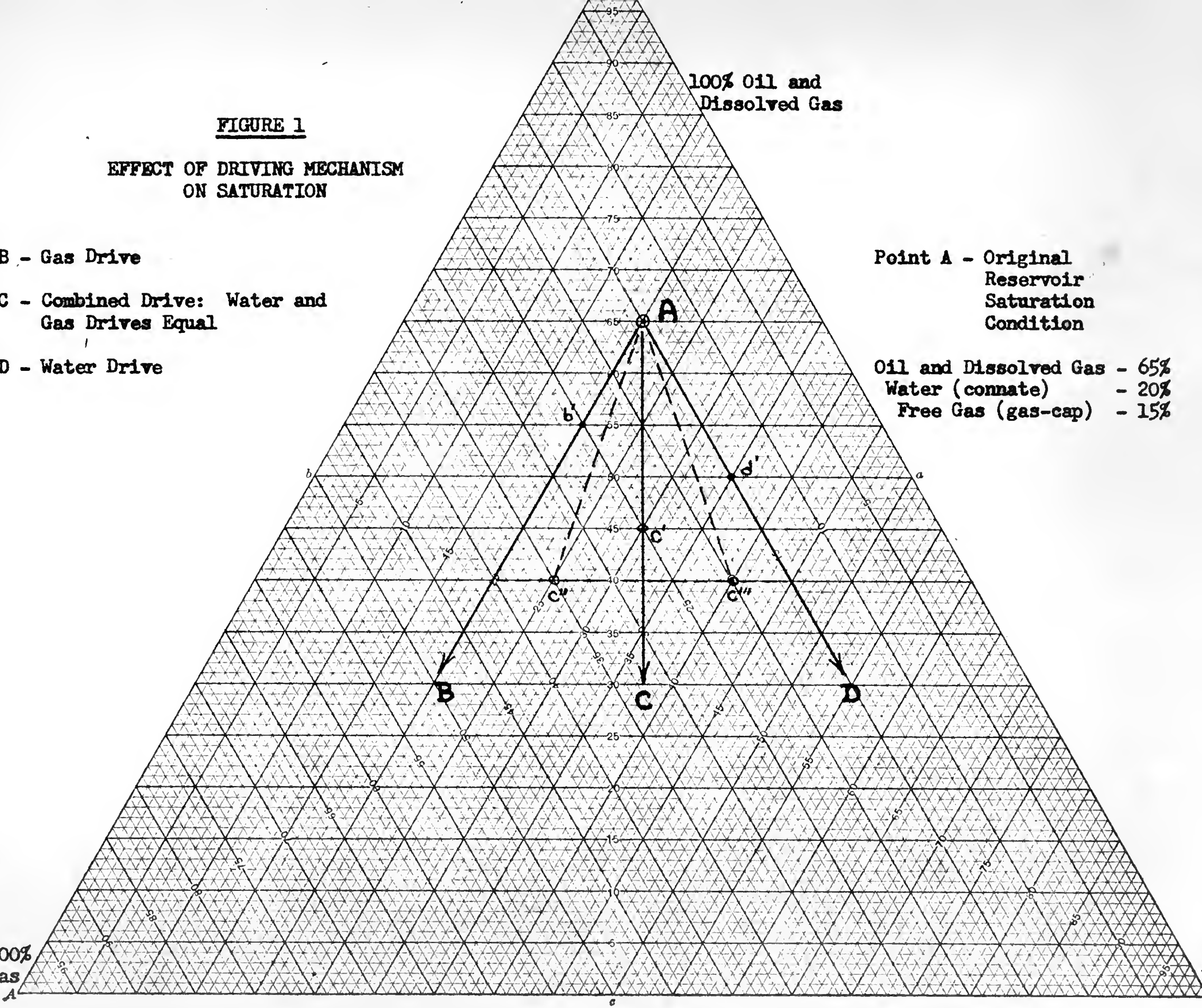
FIGURE 1

EFFECT OF DRIVING MECHANISM
ON SATURATION

AB - Gas Drive

AC - Combined Drive: Water and Gas Drives Equal

AD - Water Drive



Point A - Original Reservoir Saturation Condition

Oil and Dissolved Gas	-	65%
Water (connate)	-	20%
Free Gas (gas-cap)	-	15%

C. Calculation of Data for the Trigonic Plot

In order to obtain values for use on the trigonic plot, it is necessary to have production and laboratory data that will permit calculation of (1) original saturation conditions of the virgin reservoir, and (2) saturation conditions at any time, t, after production has started.

The equations to be used in calculating the original and susequent saturation will be derived in the following paragraphs. The nomenclature used in those equations is as follows:

V_t - total pore volume of reservoir, barrels.

V_{og} - pore volume originally occupied by oil and dissolved gas, bbls.

V_g - pore volume originally occupied by free gas (gas-cap), bbls.

V_w - pore volume originally occupied by water (connate), bbls.

v_{og} - volume of reservoir, in barrels, occupied by oil and dissolved gas after production to time t.

v_g - volume of reservoir, in barrels, occupied by free gas after production to time t.

v_w - volume of reservoir, in barrels, occupied by water after production to time t.

S_{og} - original oil and dissolved gas saturation of reservoir.

S_g - original free gas saturation of reservoir.

S_w - original water saturation of reservoir (oil and gas-cap zones).

s_{og} - oil and dissolved gas saturation at time t.

s_g - free gas saturation at time t.

s_w - water saturation at time t.

N - barrels of stock tank oil originally in place.

n - cumulative barrels of stock tank oil produced to time t.

C. Calculation of Data for the Trigonic Plot

In order to obtain values for use on the trigonic plot, it is necessary to have production and laboratory data that will permit calculation of (1) original saturation conditions of the virgin reservoir, and (2) saturation conditions at any time, t, after production has started.

The equations to be used in calculating the original and subsequent saturation will be derived in the following paragraphs. The nomenclature used in these equations is as follows:

V_t - total pore volume of reservoir, barrels.

V_{og} - pore volume originally occupied by oil and dissolved gas, bbls.

V_g - pore volume originally occupied by free gas (gas-cap), bbls.

V_w - pore volume originally occupied by water (connate), bbls.

v_{og} - volume of reservoir, in barrels, occupied by oil and dissolved gas after production to time t.

v_g - volume of reservoir, in barrels, occupied by free gas after production to time t.

v_w - volume of reservoir, in barrels, occupied by water after production to time t.

S_{og} - original oil and dissolved gas saturation of reservoir.

S_g - original free gas saturation of reservoir.

S_w - original water saturation of reservoir (oil and gas-cap zones).

s_{og} - oil and dissolved gas saturation at time t.

s_g - free gas saturation at time t.

s_w - water saturation at time t.

N - barrels of stock tank oil originally in place.

n - cumulative barrels of stock tank oil produced to time t.

B - formation volume factor; the volume occupied in barrels in the reservoir at pressure P by one barrel of stock tank oil plus the gas that will dissolve in it at that pressure.

B_o - original value of B.

G_t - volume, in SCF, of dissolved gas and free gas initially in the reservoir.

v - gas volume factor; the volume in barrels occupied in the reservoir at pressure P by one SCF of gas.

v_o - original value of v.

r - dissolved gas-oil ratio at any pressure P; the number of SCF of gas in solution per barrel of stock tank oil.

r_o - original value of r.

R_a - cumulative actual gas produced to time t, in SCF.

R_i - cumulative gas reinjected to time t, in SCF.

R_p - cumulative net gas produced to time t, in SCF. Equal to $R_a - R_i$.

W - cumulative gross water encroachment to time t, in barrels.

W_n - cumulative net water encroachment to time t, in barrels.

w_a - cumulative gross water produced to time t, in barrels.

w_i - cumulative water injected to time t, in barrels.

w_p - cumulative net water produced to time t, in barrels.

P - reservoir pressure at any time t.

P_o - original value of P.

SCF - Standard Cubic Foot: one cubic foot of gas at Standard Conditions of 60°F. and 14.7 psia.

It should be pointed out that the total pore volume of the reservoir, V_t, is the pore volume originally occupied by the connate water, by the oil and dissolved gas, and by the free gas (gas-cap), and does not include any of the pore volume of the reservoir sand that is occupied by water below the oil-water

B - formation volume factor; the volume occupied in barrels in the reservoir at pressure P by one barrel of stock tank oil plus the gas that will dissolve in it at that pressure.

B_o - original value of B.

G_o - volume, in SCF, of dissolved gas and free gas initially in the reservoir.

v - gas volume factor; the volume in barrels occupied in the reservoir at pressure P by one SCF of gas.

v_o - original value of v.

r - dissolved gas-oil ratio at any pressure P; the number of SCF of gas in solution per barrel of stock tank oil.

r_o - original value of r.

R_a - cumulative actual gas produced to time t, in SCF.

R_i - cumulative gas reinjected to time t, in SCF.

R_p - cumulative net gas produced to time t, in SCF. Equal to $R_a - R_i$.

e - cumulative gross water encroachment to time t, in barrels.

e_n - cumulative net water encroachment to time t, in barrels.

w_a - cumulative gross water produced to time t, in barrels.

w_i - cumulative water injected to time t, in barrels.

w_p - cumulative net water produced to time t, in barrels.

P - reservoir pressure at any time t.

P_o - original value of P.

SCF - Standard Cubic Feet: one cubic foot of gas at standard conditions of 60°F. and 14.7 psia.

It should be pointed out that the total pore volume of the reservoir, V_o, is the pore volume originally occupied by the connate water, by the oil and dissolved gas, and by the free gas (gas-cap), and does not include any of the pore volume of the reservoir sand that is occupied by water below the oil-water interface. The original water saturation used in the trigonic plot is due to the connate water found in the oil and gas-cap zones as determined by core analysis.

1. Determination of Oil and Dissolved Gas Saturation

The volume of the reservoir originally occupied by oil and dissolved gas is best determined from geological information, that is, the number of acre-feet of producing formation containing oil and dissolved gas. The oil-gas interface and the oil-water interface in the reservoir must be known with reasonable accuracy.

If V_t equals the total pore volume of the reservoir, V_{og} equals the pore volume originally occupied by oil and dissolved gas, and S_{og} represents the per cent saturation by oil and dissolved gas then:

$$S_{og} = V_{og}/V_t \times 100$$

The original volume of oil and dissolved gas in place is also expressed in terms of barrels of stock tank oil and the formation volume factor; so:

$$V_{og} = NB_o$$

and:

$$S_{og} = NB_o/V_t \times 100$$

As production of the reservoir proceeds, n barrels (cumulative) of stock tank oil are produced and measured under standard conditions of pressure and temperature at the surface. The amount of stock tank oil remaining in the reservoir is then (N-n) barrels, and the volume of oil and dissolved gas under the new reservoir condition is expressed as:

$$v_{og} = (N-n)B$$

and the saturation under the new conditions becomes:

$$s_{og} = (N-n)B/V_t \times 100$$

2. Determination of Free Gas Saturation

The volume of the reservoir originally occupied by free gas in the gas-cap is also best determined from geological information in the same manner interface. The original water saturation used in the trigonic plot is due to the connate water found in the oil and gas-cap zones as determined by core analysis.

1. Determination of Oil and Dissolved Gas Saturation

The volume of the reservoir originally occupied by oil and dissolved gas is best determined from geological information, that is, the number of acre-feet of producing formation containing oil and dissolved gas. The oil-gas interface and the oil-water interface in the reservoir must be known with reasonable accuracy.

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$$V_{og} = (N-n)B$$

and the saturation under the new conditions becomes:

$$S_{og} = (N-n)B/V_t \times 100$$

2. Determination of Free Gas Saturation

The volume of the reservoir originally occupied by free gas in the gas-cap is also best determined from geological information in the same manner as the volume of oil and dissolved gas. Then, if V_g equals the pore volume (in barrels) originally occupied by free gas and S_g represents the original per cent saturation by free gas:

$$S_g = V_g/V_t \times 100$$

In determining the free gas saturation as production of the reservoir proceeds, several factors must be considered. If the reservoir pressure has dropped to a value below the saturation pressure, gas in solution in the oil will evolve and become free gas. Some of this evolved free gas will enter the gas-cap, some will be produced, and some will remain in the oil zone in the free state. Each barrel of reservoir oil entering the well will also contain dissolved gas that will be separated from the oil at the surface.

If all gas, free and dissolved, originally in the reservoir is converted into a volume in cubic feet at standard conditions, then:

$$\text{Total gas (SCF)} = G_t = ((V_g/v_o)+Nr_o)$$

After R_a cumulative standard cubic feet of gas have been produced, the volume of gas remaining in the reservoir will be:

$$\text{Remaining gas (SCF)} = (G_t - R_a)$$

Of the gas remaining in the reservoir, r SCF are dissolved in each of the (N - n) barrels of oil remaining in the reservoir so the free gas remaining then will be:

$$\text{Free gas remaining (SCF)} = (G_t - R_a - (N - n)r)$$

If R_i cumulative standard cubic feet of gas have been injected into the reservoir, then the free gas remaining in the reservoir must be increased by this amount, so:

$$\text{Free gas remaining (SCF)} = (G_t - R_a - (N - n)r + R_i)$$

R_a and R_i are frequently combined into a single value called the cumulative net gas produced, R_p. $R_p = R_a - R_i$

To reduce the free gas remaining from SCF to barrels at reservoir pressure and temperature, the foregoing equation is multiplied by the gas volume as the volume of oil and dissolved gas. Thus, R'/V_1 equals the gas volume (in barrels) originally contained by free gas and S_g represents the original per cent saturation by free gas:

$$S_g = V_g/V_1 \times 100$$

In determining the free gas saturation as production of the reservoir proceeds, several factors must be considered. If the reservoir pressure has dropped to a value below the saturation pressure, gas in solution in the oil will evolve and become free gas. Part of this evolved free gas will enter the gas cap, some will be produced, and some will remain in the oil zone in the free state. Each barrel of reservoir oil entering the well will also contain dissolved gas that will be separated from the oil at the surface.

If all gas, free and dissolved, originally in the reservoir is converted into a volume in cubic feet at standard conditions, then:

$$\text{Total gas (SCF)} = G_f + G_s = (V_g/v_g)(5.615) + NR_s$$

After G_p cumulative standard cubic feet of gas have been produced, the volume of gas remaining in the reservoir will be:

$$\text{Remaining gas (SCF)} = G - G_p$$

Of the gas remaining in the reservoir, NR are dissolved in each of the $(N - N_p)$ barrels of oil remaining in the reservoir as the free gas remaining then will be:

$$\text{Free gas remaining (SCF)} = G - G_p - R(N - N_p)$$

If G_i cumulative standard cubic feet of gas have been injected into the reservoir, then the free gas remaining in the reservoir will be increased by that amount, or

$$\text{Free gas remaining (SCF)} = G - G_p + G_i - R(N - N_p)$$

G_p and G_i are frequently combined into a single value called the net cumulative gas produced, $G_{pn} = G_p - G_i$.

To reduce the free gas remaining from SCF to reservoir cubic feet at reservoir pressure and temperature, the formation volume factor, B_g, is used.

factor, v, corresponding to the reservoir pressure P. Then:

$$v_g \text{ (bbl)} = (G_t - R_p - (N - n)r)v$$

The free gas saturation, under the new reservoir conditions, is then:

$$s_g = v_g/V_t \times 100$$

3. Determination of Water Saturation

In the establishment of the total pore volume of the reservoir, it is considered that none of the pore space is initially occupied by encroached water. For this reason, the oil-water interface should be located with reasonable accuracy. The amount of connate water occupying pore space in the oil zone and gas-cap zone is determined from core analysis and electric logs. The connate water saturation is then taken as the initial water saturation of the reservoir. It is considered necessary to include this connate water saturation in the calculations, since, if some of it is eventually produced, the decrease in water saturation must be reflected in the trigonic plot. On the other hand, if no connate water is produced and water encroachment is later evident, the subsequent water saturation will be a value higher than the initial saturation which was due solely to the connate water.

During production the degree or amount of water encroachment cannot be readily measured. However, since by definition:

$$s_{og} + s_g + s_w = 100 \text{ per cent}$$

and s_{og} and s_g can be calculated from production data, it follows that:

$$s_w = 100 - (s_{og} + s_g)$$

Furthermore, when the values of s_{og} and s_g are plotted on the trigonic plot, the value of s_w is automatically established.

The establishment of the water saturation, s_w, as indicated above, is all that is necessary for the trigonic plot. However, if it is desired to determine the actual volume, in barrels, of the encroached water, the initial factor, v, corresponding to the reservoir pressure p. Then:

$$v_g \text{ (bbl)} = (G_t - R_p - (R - n)r)v$$

The free gas saturation, under the new reservoir conditions, is then:

$$s_g = v_g/V_p \times 100$$

3. Determination of Water Saturation

In the establishment of the total pore volume of the reservoir, it is considered that none of the pore space is initially occupied by encroached water. For this reason, the oil-water interface should be located with reasonable accuracy. The amount of connate water occupying pore space in the oil zone and gas-cap zone is determined from core analysis and electric logs. The connate water saturation is then taken as the initial water saturation of the reservoir. It is considered necessary to include this connate water saturation in the calculations, since, if some of it is eventually produced, the decrease in water saturation must be reflected in the trigonic plot. On the other hand, if no connate water is produced and water encroachment is later evident, the subsequent water saturation will be a value higher than the initial saturation which was due solely to the connate water.

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Furthermore, when the values of s_{og} and s_g are plotted on the trigonic plot, the value of s_w is automatically established.

The establishment of the water saturation, s_w, as indicated above, is all that is necessary for the trigonic plot. However, if it is desired to determine the actual volume, in barrels, of the encroached water, the initial and subsequent water saturations are used, since:

$$W_n = (s_w - S_w)V_t$$

W_n in this equation is the volume of the cumulative net encroached water. To obtain the cumulative gross encroached water volume, the cumulative volume of any water produced must be added to W_n, and the cumulative volume of any water injected must be deducted from W_n, so:

$$W = W_n + w_a - w_i$$

or since:

$w_a - w_i = w_p$, the cumulative net water produced, then:

$$W = W_n + w_p$$

Values for the volume of encroached water are usually calculated by using the Schilthuis material balance equation, or modifications thereof. If such values are available they can be used as a check on the water saturation obtained from the trigonic plot, since:

$$s_w = (V_w + W - w_p)/V_t$$

and subsequent water saturations are used, since

$$W_e = (S_w - S_{wi})V_p$$

W_e in this equation is the volume of the cumulative net encroached water. To obtain the cumulative gross encroached water volume, the cumulative volume of any water produced must be added to W_e, and the cumulative volume of any water injected must be subtracted from W_e, so:

$$W = W_e + W_p - W_i$$

or since:

$W_p - W_i = W_{np}$, the cumulative net water produced, then

$$W = W_e + W_{np}$$

Values for the volume of encroached water are usually calculated by using the Schilthuis material balance equation, or modifications thereof. If such values are available they can be used as a check on the water saturation obtained from the Welge's plot, since:

$$W_e = (S_w + b - S_{wi})V_p$$

IV. TRIGONAL INTERPRETATION OF ACTUAL RESERVOIRS

A. The Schuler Jones Sand Pool

1. General Description and Production History

The Schuler Jones Sand Pool, discovered in September 1937, is located in west central Union County, Arkansas. The reservoir is an anticlinal type trap, approximately four miles long, east and west, and one and one-half miles wide. Maximum closure of the reservoir is 135 feet. Average depth of production is 7,400 feet, with the gas-oil contact at -7,270 feet and the water-oil contact at -7,370 to -7,380 feet.

The reservoir rock is composed of fine to medium size sand grains and is not uniform, but consists of sandstone zones interspersed with shale. The average porosity is 20.2 per cent and the average permeability is 400 millidarcies. Connate water saturation is 35 per cent.

The original volume of the reservoir, as determined from coring and electric logging, is 154,000 acre-feet with approximately 150,000 acre-feet of oil zone and 4,000 acre-feet of gas-cap.

The field was unitized in February 1941 and a gas injection program was started in July 1941. In July 1944 a water injection program was started. From discovery until the start of gas injection the field produced approximately 19 million barrels of oil with the reservoir pressure dropping from 3548 to 1542 psia. From the start of gas injection to March 1950, the field produced approximately 30 million barrels of oil with a drop in reservoir pressure from 1542 to 1432 psia. Careful production and pressure records have been kept on this field and material balance calculations indicate approximately 100 million barrels of stock tank oil originally in place in the reservoir.

IV. TECHNICAL INTERPRETATION OF ACTUAL CASE HISTORIES

a. The Schuler Jones Sand Pool

1. General Description and Production History

The Schuler Jones Sand Pool, discovered in September 1937, is located in west central Union County, Arkansas. The reservoir is an anticlinal type trap, approximately four miles long, east and west, and one and one-half miles wide. Maximum closure of the reservoir is 135 feet. Average depth of production is 7,400 feet, with the gas-oil contact at -7,270 feet and the water-oil contact at -7,370 to -7,380 feet.

The reservoir rock is composed of fine to medium size sand grains and is not uniform, but consists of sandstone zones interspersed with shale. The average porosity is 20.2 per cent and the average permeability is 400 millidarcies. Connate water saturation is 35 per cent.

The original volume of the reservoir, as determined from coring and electric logging, is 159,000 acre-feet with approximately 155,000 acre-feet of oil zone and 4,000 acre-feet of gas-cap.

The field was unitized in February 1941 and a gas injection program was started in July 1941. In July 1944 a water injection program was started. From discovery until the start of gas injection the field produced approximately 10 million barrels of oil with the reservoir pressure dropping from 3245 to 1982 psia. From the start of gas injection to March 1950, the field produced approximately 30 million barrels of oil with a drop in reservoir pressure from 1982 to 1432 psia. Careful production and pressure records have been kept on this field and material balance calculations indicate approximately 100 million barrels of stock tank oil originally in place in the reservoir.

Produced gas has been used exclusively for reinjection, except for a period in 1944-1945 when "make up" gas was imported. During this period more gas was injected than produced, which resulted in a decrease in the cumulative net gas produced for January and July 1945.[2,3,4]

2. Trigonic Plot of Schuler Jones Sand Pool

Figure 2 is the trigonic plot for the Schuler Jones Sand Pool and covers the period of production from discovery of the pool in September 1937 to March 1950. Reservoir characteristics, fluid characteristics and production data used in calculating the values for the trigonic plot and these calculated values are tabulated in Appendix I.

3. Trigonal Interpretation of the Performance of the Schuler Jones Sand Pool

Point A on figure 2 represents the original saturation condition in the reservoir at time of discovery. This saturation condition was:

Oil and dissolved gas saturation	63.3 per cent
Free gas saturation	1.7 per cent
Water saturation	35.0 per cent

Point B represents the saturation condition in January 1942, six months after gas injection was started. Oil and dissolved gas saturation had dropped to 44.8 per cent, free gas saturation had increased to 19.6 per cent, while water saturation had remained practically constant with a value of 35.6 per cent. Since the volume of the reservoir vacated by the produced oil and dissolved gas had been occupied almost solely by free gas, it is evident that the driving mechanism producing the reservoir between points A and B was a gas drive. The line from A to B closely approximates the situation of an ideal gas drive.

Point C represents the saturation condition at a time between March and September 1947. Between points B and C, both water and free gas saturation increased, indicating a combined water and gas drive as the mechanism producing the reservoir. The trend of the line between points B and C indicates that

Produced gas has been used exclusively for reinjection, except for a period in 1944-1945 when "make up" gas was imported. During this period more gas was injected than produced, which resulted in a decrease in the cumulative net gas produced for January and July 1945.[2,3,4]

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Point C represents the saturation condition at a time between March and September 1947. Between points B and C, both water and free gas saturation increased, indicating a combined water and gas drive as the mechanism producing the reservoir. The trend of the line between points B and C indicates that the gas drive is slightly predominant over the water drive. The Displacement Index for this interval of production is 1.24/1.

Point D represents the saturation condition in March 1950. Between points C and D, the water saturation increased while the free gas saturation remained almost constant. This fact and the trend of the line between points C and D indicate that an ideal water drive was the mechanism producing the reservoir.

the gas drive is slightly predominant over the water drive. The displacement index for this interval of production is 1.24/1.

Point D represents the saturation condition in March 1950. Between points C and D, the water saturation increased while the free gas saturation remained almost constant. This fact and the trend of the line between points C and D indicate that no local water drive was the mechanism producing the reservoir.

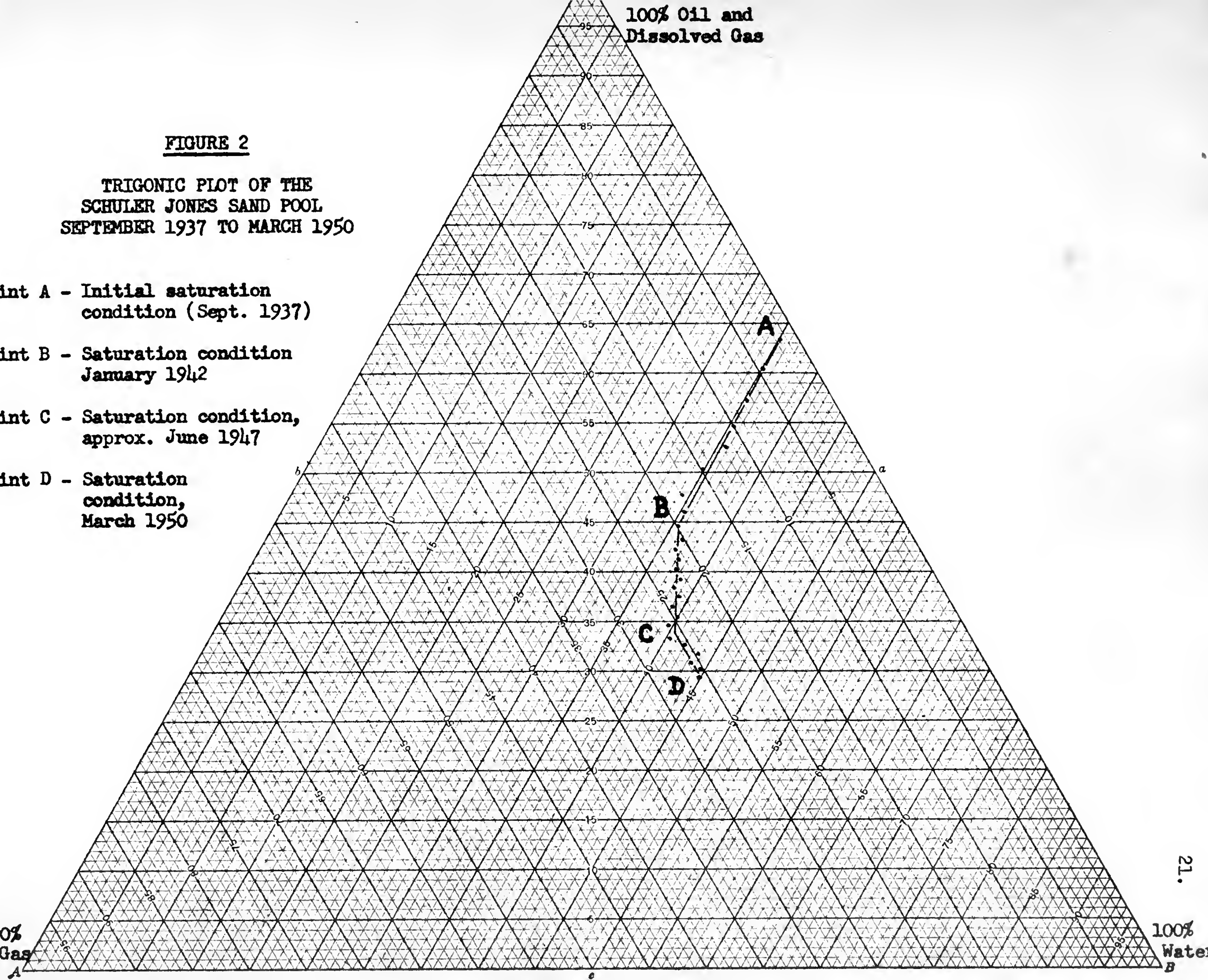


FIGURE 2

TRIGONIC PLOT OF THE
SCHULER JONES SAND POOL
SEPTEMBER 1937 TO MARCH 1950

Point A - Initial saturation condition (Sept. 1937)

Point B - Saturation condition January 1942

Point C - Saturation condition, approx. June 1947

Point D - Saturation condition, March 1950

B. The Magnolia Field Reynolds Lime Pool

1. General Description and Production History

Engineering data from the Bureau of Mines Report of Investigations 3720 (1943), and factual data from the Arkansas Oil and Gas Commission as given in Pirson[5] have been used for calculating the values for a trigonic plot of the Magnolia Field Reynolds Lime Pool.

The Magnolia Field Reynolds Lime Pool, discovered in March 1938, is located in Columbia County, Arkansas. The reservoir is on a symmetrical anticlinal fold, 6 miles long and 1 1/2 miles wide. Maximum closure of the reservoir is 321 feet.

The reservoir rock is an oölitic limestone varying from a porous, highly permeable, sometimes cavernous oölite to dense, granular limestone of low porosity and permeability. Average porosity is estimated at 16.82 per cent,[5] and average permeability is 1,500 millidarcies. Connate water saturation is 20.0 per cent.

The original volume of the reservoir is 419,550 acre-feet with 345,550 acre-feet in the oil zone and 74,000 acre feet in the gas-cap.

From discovery until June 1948, the reservoir had produced approximately 53 million barrels of oil and 52 billion cubic feet of gas, with a drop in reservoir pressure from 3,480 to 2,818 psia. Volumetric calculations indicate that approximately 244 million barrels of stock tank oil were originally in place in the reservoir.

2. Trigonic Plot of the Magnolia Field Reynolds Lime Pool

Figure 3 is the trigonic plot of the Magnolia Field Reynolds Lime Pool, and covers the period of production from discovery in March 1938 to June 1948. Reservoir characteristics, fluid characteristics and production data used in calculating the values for the trigonic plot and these calculated values are tabulated in Appendix II.

D. The Magnolia Field Reynolds Lime Pool

1. General Description and Production History

Engineering data from the Bureau of Mines Report of Investigations 3720 (1943), and factual data from the Arkansas Oil and Gas Commission as given in Pirson[5] have been used for calculating the values for a trigonic plot of the Magnolia Field Reynolds Lime Pool.

The Magnolia Field Reynolds Lime Pool, discovered in March 1938, is located in Columbia County, Arkansas. The reservoir is on a symmetrical anticlinal fold, 6 miles long and 1 1/2 miles wide. Maximum closure of the reservoir is 321 feet.

The reservoir rock is an oolitic limestone varying from a porous, highly permeable, sometimes cavernous oolite to a dense, granular limestone of low porosity and permeability. Average porosity is estimated at 16.52 per cent[5] and average permeability is 1,500 millidarcies. Connate water saturation is 20.0 per cent.

The original volume of the reservoir is 419,550 acre-feet with 345,550 acre-feet in the oil zone and 74,000 acre feet in the gas-cap.

From discovery until June 1946, the reservoir had produced approximately 53 million barrels of oil and 52 billion cubic feet of gas, with a drop in reservoir pressure from 3,600 to 2,315 psia. Volumetric calculations indicate that approximately 244 million barrels of stock tank oil were originally in place in the reservoir.

2. Trigonic Plot of the Magnolia Field Reynolds Lime Pool

Figure 5 is the trigonic plot of the Magnolia Field Reynolds Lime Pool and covers the period of production from discovery, in March 1938 to June 1946. Reservoir characteristics, fluid characteristics and production data used in calculating the values for the trigonic plot and those calculated values are tabulated in Appendix II.

3. Trigonal Interpretation of the Performance of the Magnolia Field Reynolds Lime Pool

Point A on figure 3 represents the original saturation condition in the reservoir at time of discovery. This saturation condition was:

Oil and dissolved gas saturation	65.9 per cent
Free gas saturation	14.1 per cent
Water saturation	20.0 per cent

Point B represents the saturation condition at approximately June 1944, almost six years after discovery of the reservoir. Oil and dissolved gas saturation had dropped to 54.8 per cent, free gas saturation had increased to 20.3 per cent, and water saturation had increased to 24.9. The increase in both the free gas and the water saturation indicate that a combined water and gas drive was the driving mechanism producing the reservoir during this period. The trend of the line between points A and B further indicates that the magnitude of the gas drive was about equal to the magnitude of the water drive. The Displacement Index for this interval of production is 1.06/1.

Point C represents the saturation condition on June 30, 1948. Between points B and C the water saturation increased while the free gas saturation remained almost constant. This fact and the trend of the line between points B and C indicates that a water drive, approaching the ideal, was the mechanism producing the reservoir. Displacement Index for this interval of production is 1/10.4.

3. Trigonal Interpretation of the Performance of the Magnolia Field Reynolds Lime Pool

Point A on figure 3 represents the original saturation condition in the reservoir at time of discovery. This saturation condition was:

Oil and dissolved gas saturation	65.9 per cent
Free gas saturation	14.1 per cent
Water saturation	20.0 per cent

Point B represents the saturation condition at approximately June 1944, almost six years after discovery of the reservoir. Oil and dissolved gas saturation had dropped to 54.8 per cent, free gas saturation had increased to 20.3 per cent, and water saturation had increased to 24.9. The increase in both the free gas and the water saturation indicate that a combined water and gas drive was the driving mechanism producing the reservoir during this period. The trend of the line between points A and B further indicates that the magnitude of the gas drive was about equal to the magnitude of the water drive. The Displacement Index for this interval of production is 1.05/1.

Point C represents the saturation condition on June 30, 1948. Between points B and C the water saturation increased while the free gas saturation remained almost constant. This fact and the trend of the line between points B and C indicates that a water drive, approaching the ideal, was the mechanism producing the reservoir. Displacement Index for this interval of production is 1/30.4.

FIGURE 3

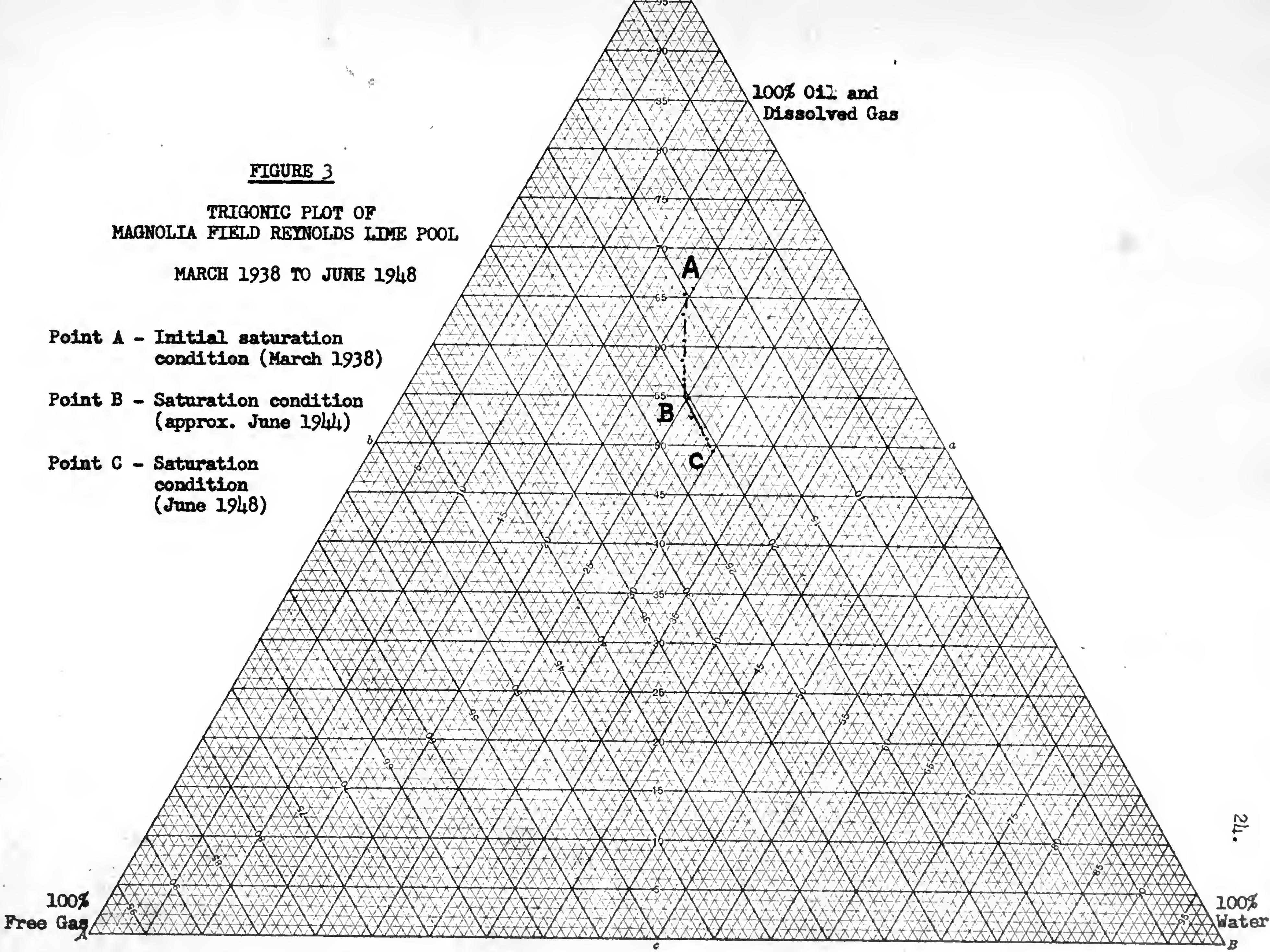
TRIGONIC PLOT OF
MAGNOLIA FIELD REYNOLDS LIME POOL

MARCH 1938 TO JUNE 1948

Point A - Initial saturation condition (March 1938)

Point B - Saturation condition (approx. June 1944)

Point C - Saturation condition (June 1948)



C. Comparison of the Performance of the Two Reservoirs

The driving mechanism for the initial phase of production of the Schuler Jones Sand Pool (line AB, figure 2) was mainly a dissolved gas drive. This is also indicated by the appreciable drop in reservoir pressure during this phase. The driving mechanism for the second phase of production (line BC, figure 2) was a combined water and gas drive, and for the third phase (line CD, figure 2) was a water drive.

The driving mechanism for the initial phase of production of the Magnolia Field Reynolds Lime Pool (line AB, figure 3) was a combined water and gas drive, and for the second phase (line BC, figure 3) was a water drive. The immediate driving effect of the water drive in the Magnolia Field Reynolds Lime Pool would indicate a harder water drive, in this pool, than in the Schuler Jones Sand Pool. The higher permeability and the existence of cavernous spaces in the Reynolds limestone would act, in part, to assist in the rapid encroachment of driving water.

During the combined water and gas drive phase and the water drive phase, the performance of both reservoirs was remarkably similar. After the oil and dissolved gas saturation had been decreased by 10 per cent to 12 per cent, by combined water and gas drive, the water drive took over as the driving mechanism producing the reservoir. This change-over from a combined drive to a water drive possibly is due to the increase in the water relative permeability that accompanies the increase in water saturation. However, it must be pointed out that the water saturation indicated by the trigonic plot is not the water saturation throughout the entire reservoir. The water saturation in the portion of the oil zone invaded by water will be very high, while the water saturation in the uninvaded portion and the gas-cap will be due to the connate water only. It is the

C. Comparison of the Performance of the Two Reservoirs

The driving mechanism for the initial phase of production of the Schuler Jones Sand Pool (line AB, Figure 2) was mainly a dissolved gas drive. This is also indicated by the appreciable drop in reservoir pressure during this phase. The driving mechanism for the second phase of production (line BC, Figure 2) was a combined water and gas drive, and for the third phase (line CD, Figure 2) was a water drive.

The driving mechanism for the initial phase of production of the Magnolia Field Reynolds Lime Pool (line AB, Figure 3) was a combined water and gas drive, and for the second phase (line BC, Figure 3) was a water drive. The immediate driving effect of the water drive in the Magnolia Field Reynolds Lime Pool would indicate a harder water drive, in this pool, than in the Schuler Jones Sand Pool. The higher permeability and the existence of cavernous spaces in the Reynolds limestone would act, in part, to assist in the rapid encroachment of driving water.

During the combined water and gas drive phase and the water drive phase, the performance of both reservoirs was remarkably similar. After the oil and dissolved gas saturation had been decreased by 10 per cent to 12 per cent, by combined water and gas drive, the water drive took over as the driving mechanism producing the reservoir. This change-over from a combined drive to a water drive possibly is due to the increase in the water relative permeability that accompanies the increase in water saturation. However, it must be pointed out that the water saturation indicated by the triangle plot is not the water saturation throughout the entire reservoir. The water saturation in the portion of the oil zone invaded by water will be very high, while the water saturation in the un-invaded portion and the gas-cap will be due to the connate water only. It is the high water relative permeability, resulting from the high water saturation in the invaded zone, that assists in making the water drive predominate.

high water relative permeability, resulting from the high water saturation in the invaded zone, that assists in making the water drive predominate.

V. DISCUSSION

While the trigonic plot will provide a means of interpreting the over-all performance of a producing petroleum reservoir, it has certain definite limitations.

The primary limitation of the trigonic plot is that it will not distinguish of itself between a dissolved gas drive and an expanding gas-cap drive. This limitation applies to both the ideal gas drive situation and to the gas drive portion of the combined water and gas drive situation.

In using the trigonic plot, it must be kept constantly in mind that the saturations given by the plot are the gross saturations for the entire reservoir and are not the saturations in different parts of the reservoir. The trigonic plot does not reveal what portion of the free gas is in the gas-cap and what portion is in the oil zone in the free state. Similarly, the trigonic plot will not reveal how much oil remains in that portion of the reservoir invaded by encroaching or driving water. This is particularly important since it is the oil recovered that pays for the cost of production.

In the development of the trigonic plot as a means of interpreting reservoir performance, a theoretical reservoir having free gas in a gas-cap and a water drive was assumed. The actual reservoirs used for illustration also had gas-caps and water drives. The trigonic plot can be used for a reservoir that has a water drive and no gas-cap, if, at any time during production, free gas is present in the reservoir. Where there is no water drive, the saturation picture on the trigonic plot will follow the ideal gas drive line AB, figure 1.

It should also be pointed out that, in the final stages of primary recovery, where the reservoir pressure is low, the water drive will produce or

expel free gas as well as oil and dissolved gas. On the trigonic plot, this situation would result in a trend of saturation conditions indicating that the water drive is exceeding the limit established for the ideal water drive.

In respect to the residual oil left by a water drive, it is of interest to note the results obtained in the laboratory by Holmgren[6] who used gas and water drives on a long core of Nellie Bly sandstone, and then measured the residual oil. Holmgren concluded that: "Maintenance of initial gas saturation by gas injection, together with an increase in water saturation by water input, results in lower final oil saturation." The effects of free gas saturation on oil recovery by water drive has been investigated by Holmgren and Morse[7], using the long core of Nellie Bly sandstone. They conclude that:

> "The production of oil by water flooding can be substantially increased by the maintenance of free gas saturation in the reservoir during the flooding operation. This effect is accomplished by the alteration of oil relative permeability characteristics and the occupation by gas of pore space that would otherwise be filled with residual oil."

If the foregoing conclusions are applied to the trigonic plot of the performance of a reservoir, an indication of ultimate oil recovery can be obtained. That is, if the trigonic plot shows an appreciable free gas saturation during the water drive phase a higher ultimate recovery can be expected than if no free gas were present. However, it must be remembered that the free gas saturation given by the trigonic plot does not distinguish between free gas in the gas-cap and free gas in the oil zone.

It appears then, that, in the case of an established active water drive, it might be desirable to insure the presence of free gas in the oil zone by gradual or periodic flash reduction of the reservoir pressure. This would have the same effect as maintaining, to a degree, a combined water and gas drive in the reservoir.

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VI. CONCLUSIONS

It can be concluded that, within its limitations, the trigonic plot of the performance of a producing petroleum reservoir will:

(a) provide a visual representation of the material balance of the reservoir components;

(b) indicate the nature of the driving mechanism producing the reservoir;

(c) indicate the relative magnitudes of the two driving forces when a combined drive mechanism is producing the reservoir;

(d) indicate the change from one driving mechanism to another;

or, to summarize, will provide the means for making a trigonal interpretation of reservoir performance.

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APPENDIX I

TABLE I

SCHULER JONES SAND POOL CHARACTERISTICS

1. Reservoir Characteristics[4]

Total Reservoir volume	154,000 acre-feet
Original oil reservoir volume	150,000 acre-feet
Original gas-cap volume	4,000 acre-feet
Porosity (average)	20.2 per cent
Connate water saturation	35.0 per cent

2. Fluid Characteristics[4]

Original reservoir pressure	3548 psia.
Original reservoir temperature	198°F.
Original dissolved gas-oil ratio	770 cu. ft. per bbl.
Original formation volume factor	1.452
Original gas volume factor	0.000825

3. Equations from literature[4] used for determining dissolved gas-oil ratio, formation volume factor and gas volume factor at any pressure P, in lbs. per sq. in. abs., above 300psia

$$r = 0.0334P + 18.65 \text{ cu. ft./cu. ft.}$$

$$B = 8.0 \times 10^{-5}P + 1.168$$

$v = 0.062P - 4$ in SCF of gas equivalent to one cubic foot of gas at reservoir conditions

4. Volumes used in calculations for trigonic plot based on volumetric calculation from geologic data

V_t	- Total pore volume of reservoir	241,340,000 barrels
V_{og}	- Pore volume originally occupied by oil and dissolved gas	152,790,000 barrels
V_g	- Pore volume originally occupied by free gas in gas-cap	4,080,000 barrels
V_w	- Pore volume originally occupied by connate water	84,470,000 barrels
N	- Stock tank oil originally in place	105,270,000 barrels
G_t	- Dissolved and free gas originally in place	85.96 billion cu. ft.

TABLE II

PRODUCTION DATA[4] AND SATURATION CALCULATIONS: SCHULER JONES SAND POOL

End of Month	Reservoir Pressure, P; psia	Cumulative Oil Produced n; 10^6 bbl	(N - n) 10^6 bbl	B	(N-n) B 10^6 bbl	$(N-n)B/V_t$ s_{og}; %	Cumulative Net Gas Produced R_p; 10^9 SCF	Dissolved Gas Oil Ratio r: SCF/bbl	(N - n)r 10^9 SCF	R_p + (N - n)r 10^9 SCF	$G_t-[R_p+(N-n)r]$ 10^9 SCF	v	$(G_t-[R_p+(N-n)r])v$ $= v_g$; 10^6 bbl	v_g/V_t $= s_g$%	$100-(s_{og}+s_g)$ s_w; %
September 1937	3548	--	--	--	--	63.3	--	--	--	--	--	--	--	1.7	35.0
July 1938	3153	2.818	102.45	1.420	145.84	60.3	2.59	695	71.20	73.79	12.17	0.00093	11.32	4.7	35.0
January 1939	2813	6.030	99.24	1.393	138.24	57.3	5.87	631	62.62	68.49	17.47	0.00105	18.34	7.6	35.1
July 1939	2533	8.751	96.52	1.371	132.33	54.8	9.22	579	55.89	65.11	20.85	0.00116	24.19	10.0	35.2
January 1940	2318	11.259	94.01	1.353	127.20	52.7	13.17	539	50.67	63.84	22.12	0.00128	28.32	11.7	35.6
July 1940	1978	13.998	91.27	1.326	121.06	50.2	18.63	475	43.35	61.99	23.97	0.00151	36.20	15.0	34.8
January 1941	1658	16.552	88.72	1.301	115.42	47.8	24.97	415	36.82	61.79	24.17	0.00180	43.51	18.0	34.2
July 1941	1542	19.006	86.26	1.291	111.36	46.1	28.74	394	33.99	62.73	23.23	0.00194	45.07	18.7	35.2
January 1942	1524	21.474	83.80	1.290	108.10	44.8	29.33	390	32.68	62.01	23.95	0.00197	47.18	19.6	35.6
July 1942	1510	23.722	81.55	1.289	105.12	43.6	29.79	388	31.64	61.43	24.53	0.00199	48.81	20.2	36.2
January 1943	1497	25.927	79.34	1.288	102.19	42.3	30.05	385	30.55	60.55	25.41	0.00201	51.07	21.3	36.4
July 1943	1490	27.922	77.35	1.287	99.55	41.3	30.21	384	29.70	59.91	26.05	0.00202	52.62	21.8	36.9
January 1944	1496	29.810	75.46	1.288	97.19	40.3	30.26	385	29.05	59.31	26.65	0.00201	53.57	22.2	37.5
July 1944	1496	31.617	73.65	1.288	94.86	39.3	30.48	385	28.35	58.83	27.13	0.00201	54.53	22.6	38.1
January 1945	1489	33.350	71.92	1.287	92.56	38.4	30.42	384	27.62	58.03	27.93	0.00202	56.42	23.4	38.2
July 1945	1498	34.987	70.28	1.288	90.52	37.5	30.37	385	27.06	57.43	28.53	0.00201	57.35	23.8	38.7
March 1946	1488	37.161	68.11	1.287	87.66	36.3	30.51	383	26.09	56.60	29.36	0.00202	59.31	24.6	39.1
August 1946	1494	38.538	66.73	1.287	85.88	35.6	30.56	385	25.69	56.23	29.71	0.00201	59.92	24.7	39.7
March 1947	1471	40.432	64.84	1.286	83.38	34.6	30.85	380	24.64	55.49	30.47	0.00205	62.46	25.9	39.5
September 1947	1461	42.064	63.21	1.285	81.22	33.7	31.38	378	23.89	55.27	30.69	0.00206	63.22	26.2	40.1
March 1948	1454	43.698	61.57	1.284	79.60	32.8	33.17	377	23.21	56.38	29.58	0.00207	61.23	25.4	41.8
September 1948	1474	45.319	59.95	1.286	77.10	31.9	33.81	381	22.84	56.65	29.32	0.00204	59.81	24.8	43.3
March 1949	1429	46.898	58.37	1.282	74.83	31.0	34.57	372	21.71	56.28	29.68	0.00211	62.62	25.9	43.1
September 1949	1437	48.197	57.07	1.283	73.19	30.3	35.23	374	21.34	56.58	29.39	0.00210	61.72	25.3	44.4
March 1950	1432	49.412	55.86	1.283	71.67	29.7	35.30	373	20.84	56.14	29.82	0.00210	62.63	25.9	44.4

TABLE III

CALCULATED SATURATION VALUES USED FOR TRIGONIC PLOT OF SCHULER JONES SAND POOL

End of Month	S_{og} Per Cent	S_g Per Cent	S_w Per Cent
September 1937 (initial)	63.3	1.7	35.0
July 1938	60.3	4.7	35.0
January 1939	57.3	7.6	35.1
July 1939	54.8	10.0	35.2
January 1940	52.7	11.7	35.6
July 1940	50.2	15.0	34.8
January 1941	47.8	18.0	34.2
July 1941	46.1	18.7	35.2
January 1942	44.8	19.6	35.6
July 1942	43.6	20.2	36.2
January 1943	42.3	21.3	36.4
July 1943	41.3	21.8	36.9
January 1944	40.3	22.2	37.5
July 1944	39.3	22.6	38.1
January 1945	38.4	23.4	38.2
July 1945	37.5	23.8	38.7
March 1946	36.3	24.6	39.1
August 1946	35.6	24.7	39.7
March 1947	34.6	25.9	39.5
September 1947	33.7	26.2	40.1
March 1948	32.8	25.4	41.8
September 1948	31.9	24.8	43.3
March 1949	31.0	25.9	43.1
September 1949	30.3	25.3	44.4
March 1950	29.7	25.9	44.4

TABLE XII

CALCULATED SATURATION VALUES USED FOR TRIGONIC PLOT OF

SCHULER JONES SAND POOL.

End of Month	S_o Per Cent	S_g Per Cent	S_w Per Cent
September 1937 (initial)	63.3	1.7	35.0
July 1938	60.3	4.7	35.0
January 1939	57.3	7.6	35.1
July 1939	54.8	10.0	35.2
January 1940	52.7	11.7	35.6
July 1940	50.2	15.0	34.8
January 1941	47.8	18.0	34.2
July 1941	46.1	18.7	35.2
January 1942	44.8	19.6	35.6
July 1942	43.6	20.2	36.2
January 1943	42.3	21.3	36.4
July 1943	41.3	21.8	36.9
January 1944	40.3	22.2	37.5
July 1944	39.3	22.6	38.1
January 1945	38.4	23.4	38.2
July 1945	37.5	23.8	38.7
March 1946	36.3	24.6	39.1
August 1946	35.6	24.7	39.7
March 1947	34.6	25.9	39.5
September 1947	33.7	26.2	40.1
March 1948	27.8	25.4	46.8
September 1948	31.9	24.8	43.3
March 1949	31.0	25.5	43.5
September 1949	30.3	25.3	44.4
March 1950	29.7	25.9	44.4

APPENDIX II

TABLE IV

MAGNOLIA FIELD REYNOLDS LIME POOL CHARACTERISTICS

1. Reservoir Characteristics[5]

Total reservoir volume	419,550 acre-feet
Original oil reservoir volume	345,550 acre-feet
Original gas-cap volume	74,000 acre-feet
Porosity (average)	16.82 per cent
Connate water saturation	20.00 per cent

2. Fluid Characteristics[5]

Original reservoir pressure	3,480 psia
Original reservoir temperature	206°F.
Original dissolved gas-oil ratio	855 cu. ft. per bbl
Original formation volume factor	1.476
Original gas volume factor	0.000895

3. Volumes used in calculations for trigonic plot based on volumetric calculations from geologic data

V_t - Total pore volume of reservoir	547,500,000 barrels
V_{og} - Pore volume originally occupied by oil and dissolved gas	360,700,000 barrels
V_g - Pore volume originally occupied by free gas in gas-cap	77,300,000 barrels
V_w - Pore volume originally occupied by connate water	109,500,000 barrels
N - Stock tank oil originally in place	244,400,000 barrels
G_t - Dissolved and free gas originally in place	295.3 billion cu. ft.

TABLE IV

MAGNOLIA FIELD SMACKOVER LIME POOL CHARACTERISTICS

1. Reservoir Characteristics[5]

Total reservoir volume	419,550 acre-feet
Original oil reservoir volume	345,550 acre-feet
Original gas-cap volume	74,000 acre-feet
Porosity (average)	16.82 per cent
Connate water saturation	20.00 per cent

2. Fluid Characteristics[5]

Original reservoir pressure	3,600 psia
Original reservoir temperature	200°F.
Original dissolved gas-oil ratio	755 cu. ft. per bbl
Original formation volume factor	1.475
Original gas volume factor	0.003925

3. Volumes used in calculations for trigonic plot based on volumetric calculations from geologic data

V_t – Total pore volume of reservoir	547,400,000 barrels
V_{og} – Pore volume originally occupied by oil and dissolved gas	360,700,000 barrels
V_g – Pore volume originally occupied by free gas in gas-cap	77,300,000 barrels
V_w – Pore volume originally occupied by connate water	109,500,000 barrels
N – Stock tank oil originally in place	244,500,000 barrels
G_t – Dissolved and free gas originally in place	295.3 billion cu. ft.

TABLE V

PRODUCTION DATA AND SATURATION CALCULATIONS: MAGNOLIA FIELD REYNOLDS LIME POOL

End of Month	Reservoir Pressure P; psia	Cumulative Oil Produced n; 10^6 bbl	(N - n) 10^6 bbl	B	(N - n) B 10^6 bbl	(N - n)B/V_t = s_{og}; %	Dissolved gas-oil ratio r; SCF/bbl	(N - n)r 10^6 bbl	Cumulative Gas Produced R_a; 10^9SCF	R_a + (N - n)r 10^9 SCF	G_t-[R_a+(N-n)r] 10^9 SCF	v	(G_t-[R_a+(N-n)r])v = v_g; 10^6 bbl	v_g/V_t = s_g %	100-(s_{og}+s_g) = s_w; %
Initial	3480	--	--	--	--	65.9	--	--	--	--	--	--	--	14.1	20.0
June 1939	3385	1.0	243.4	1.466	356.8	65.2	833	202.8	0.9	203.7	91.6	0.00091	83.4	15.2	19.6
June 1940	3303	7.5	236.9	1.458	345.8	63.1	814	192.8	6.6	199.4	95.9	0.00093	89.2	16.3	20.6
June 1941	3190	14.8	229.6	1.446	332.0	60.6	788	180.9	13.1	194.0	101.3	0.00095	96.2	17.6	21.8
June 1942	3093	21.6	222.8	1.436	319.9	58.4	766	170.7	19.1	189.8	105.5	0.00098	103.4	18.9	22.7
June 1943	3030	27.8	216.6	1.428	309.3	56.5	751	162.7	25.4	188.1	107.2	0.00100	107.2	19.6	23.9
June 1944	2975	33.5	210.9	1.423	300.1	54.8	738	155.6	31.2	186.8	108.5	0.00101	109.6	20.0	25.2
June 1945	2899	38.8	205.6	1.415	289.5	52.9	720	147.3	36.8	184.1	111.2	0.00103	114.5	20.9	26.2
June 1946	2883	43.6	200.8	1.413	283.7	51.8	717	144.1	42.0	186.1	109.2	0.00103	112.5	20.5	27.7
June 1947	2850	48.3	196.1	1.410	276.5	50.5	710	139.2	47.2	186.4	108.9	0.00104	113.3	20.7	28.8
June 1948	2818	52.8	191.6	1.407	269.6	49.2	702	134.5	52.2	186.7	108.6	0.00105	114.0	20.8	30.0

TABLE VI

CALCULATED SATURATION VALUES USED FOR TRIGONIC PLOT OF

MAGNOLIA FIELD REYNOLDS LIME POOL

End of Month	s_{og} Per Cent	s_g Per Cent	s_w Per Cent
March 1938 (initial)	65.9	14.1	20.0
June 1939	65.2	15.2	19.6
June 1940	63.1	16.3	20.6
June 1941	60.6	17.6	21.8
June 1942	58.4	18.9	22.7
June 1943	56.5	19.6	23.9
June 1944	54.8	20.0	25.2
June 1945	52.9	20.9	26.2
June 1946	51.8	20.5	27.7
June 1947	50.5	20.7	28.8
June 1948	49.2	20.8	30.0

TABLE VI

CALCULATED SATURATION VALUES USED FOR TRIANGULAR PLOT OF

MAGNOLIA FIELD REYNOLDS LIME POOL

End of Month	S_o Per Cent	S_g Per Cent	S_w Per Cent
March 1938 (initial)	65.9	14.1	20.0
June 1939	65.2	15.2	19.6
June 1940	63.1	16.3	20.6
June 1941	60.6	17.6	21.8
June 1942	60.4	16.9	22.7
June 1943	56.5	19.6	23.9
June 1944	54.8	20.0	25.2
June 1945	52.9	20.9	26.2
June 1946	51.8	20.5	27.7
June 1947	50.5	20.7	28.8
June 1948	49.2	20.8	30.0

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